JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 112, A10306, doi:10.1029/2006JA012228, 2007

Ionospheric responses to the October 2003 superstorm: Longitude/local time effects over equatorial low and middle latitudes

Mangalathayil A. Abdu,[1] Takashi Maruyama,[2] Inez S. Batista,[1] Susumo Saito,[2] and Maho Nakamura[2]

Received 18 December 2006; revised 20 April 2007; accepted 13 July 2007; published 19 October 2007.

[1] Ionospheric responses to the major magnetic storm disturbances of October 2003 are investigated using database selected in the Brazilian and Japanese-Asian longitude sectors. Data obtained from latitudinally spaced digisondes in the equatorial and low-latitude sites in Brazil and from the Asian and Japanese ionosonde network, the total electron content data from the extensive Japanese GPS receiver chain, and magnetometer data from the Pacific equatorial electrojet stations are analyzed during the period 28–31 October. Prompt penetrating (PP) dawn-dusk polar cap electric fields produce large *F* region plasma uplift on the dayside and eveningside, while the associated westward electric field on the nightside produces large downdraft of the *F* region plasma, and causes development of westward electrojet current, observed for the first time. Episodes of PP electric field effects appear to be of larger intensity over Brazil than over Asian longitudes. Equatorial anomaly, development due to undershielding as well as overshielding electric fields, was observed in the Brazilian and in the Asian sectors. Disturbance dynamo electric field causes large nighttime *F* layer uplifts that are modulated by strong meridional winds in both sectors. The disturbance electric field local time variation patterns are compared with the results of recent global model (MTIEGCM) simulation by Richmond et al. (2003) and validated in some cases. Transients of transequatorial winds, flipping direction from southward to northward, in the widely separated longitude sectors, were diagnosed to be present toward the final recovery phase of the storm. These results are presented and discussed in this paper.

Citation: Abdu, M. A., T. Maruyama, I. S. Batista, S. Saito, and M. Nakamura (2007), Ionospheric responses to the October 2003 superstorm: Longitude/local time effects over equatorial low and middle latitudes, *J. Geophys. Res.*, *112*, A10306, doi:10.1029/2006JA012228.

1. Introduction

[2] Ionospheric responses during magnetic storms/substorms are indicative of the efficiency of the coupling processes that underlie the impulsive transfer of energy and mass through solar wind shocks with the magnetosphere. During intense storms drastic modifications to dynamics, electrodynamics and chemistry of the Earth's atmosphere-ionosphere system take place on a global scale. The ionospheric responses over equatorial and low latitudes are known to results from the consequent disturbances in the electric fields and thermospheric dynamics that propagate from polar to equatorial latitudes. The interplanetary and polar electric fields promptly penetrate to the equatorial latitudes as a dawn-dusk electric field during the onset and growth phases of a substorm event until partially balanced, by the development of the shielding layer in the inner magnetosphere [*Vasyliunas*, 1972; *Jaggi and Wolf*, 1973; *Kelley et al.*, 1979], with timescales of the order of an hour to several hours. Rapidly changing polar electric fields promptly penetrate to equatorial latitude unaffected by the shielding layer [e.g., *Kikuchi et al.*, 1996]. The prompt penetrating electric field has eastward (westward) polarity on the day (night) side. At the substorm recovery the electric field, due to the shielding layer that remains, penetrates to equatorial latitudes as an overshielding electric field with opposite polarity [see, e.g., *Kelley et al.*, 1979; *Fejer et al.*, 1990]. The ion convection under large high-latitude electric fields can cause accelerations of the neutrals leading to equatorward disturbance winds while the continuing energy input causes heating of the high-latitude I-T system whereby atmospheric disturbances propagate to lower latitudes in the form of gravity waves (TIDs) or traveling atmospheric disturbances (TADs) including disturbances in thermospheric winds [e.g., *Prolss*, 1997; *Fuller-Rowell et al.*, 2002]. They produce longer-lasting wind dynamo electric fields that begin to dominate the low-latitude electrodynamic

[1]Instituto Nacional de Pesquisas Espaciais, Divisao de Aeronomia, São José dos Campos, Sao Paulo, Brazil.
[2]National Institute of Information and Communication Technology, Tokyo, Japan.

0148-0227/07/2006JA012228

processes within a few hours from the onset of a storm and continues for several hours well into, and often beyond, the storm recovery [*Blanc and Richmond*, 1980; *Sastri*, 1988; *Abdu et al.*, 1997; *Scherliess and Fejer*, 1997; *Richmond et al.*, 2003; *Abdu et al.*, 2006b]. The equatorial and low-latitude ionospheric phenomenology is drastically modified by the prompt penetration electric field (PPE) and disturbance dynamo electric field (DDE) that have in general opposite polarity local time dependences. Therefore the equatorial ionization anomaly (EIA), the electrojet current (EEJ) and the plasma bubble irregularity/equatorial spread *F* (ESF) processes, can be greatly enhanced or inhibited under the competing influences of these electric fields. A PPE can cause large dayside enhancement in the total electron content (TEC) as observed by satellite borne and ground-based GPS receivers [*Tsurutani et al.*, 2004; *Maruyama et al.*, 2004] that can be recognized as a TEC storm [*Maruyama et al.*, 2004]. The simultaneous response on the nightside is expected to be a decrease of the TEC. An important characteristic of a TEC storm, especially during a major storm event, is noted as large latitudinal expansion and intensification of the EIA [*Abdu*, 1997; *Mannucci et al.*, 2005; *Lin et al.*, 2005a, 2005b; *Zhao et al.*, 2005]. On the other hand a DDE of westward polarity could considerably reduce the dayside TEC [*Tsurutani et al.*, 2004] and cause contraction of the EIA, while that of eastward polarity could cause large *F* layer uplift during night hours [e.g., *Sobral et al.*, 1997; *Abdu et al.*, 1997] resulting in intensification of the EIA [*Fuller-Rowell et al.*, 2002].

[3] The overall intensity of the ionospheric responses should depend upon the power of the storm energy input in the magnetosphere ionosphere system and hence on the intensity of the causative solar–interplanetary event. During the major storm of March 1989, the strong prompt penetrating (PP) eastward electric fields (>5 mV m^{-1}) that penetrated to equatorial latitudes caused large uplift of the postsunset *F* region plasma in Brazilian Atlantic sector [*Batista et al.*, 1991] as part of a giant plasma fountain that produced severe depletion of equatorial plasma as observed in the DMSP satellite orbit [*Greenspan et al.*, 1991] and large poleward expansion of the equatorial anomaly [*Abdu*, 1997] as observed in the TEC measured in geostationary satellite propagation paths in the American sector. Such large poleward expansion of the equatorial anomaly during intense storms is suspected to constitute the plasma source for the recently identified phenomenon known as storm enhanced density (SED) and the associated plasmaspheric TEC plumes observed over middle latitude [*Foster et al.*, 2005; *Immel et al.*, 2005].

[4] The intense storms of October–November 2003 were of major storm category, having been produced by the fastest coronal mass ejection (CME) events of solar cycle 23, which originated from three active regions close to the middle of the solar disk [*Gopalswamy et al.*, 2005]. The major solar eruptions with unusually high X-ray flux that occurred at 1110 UT on 28 October that was of X17 class and another one of X10 that occurred at 2049 UT on 29 October were responsible for the two major storm events that started with SSCs at 0610 UT 29 October and at 1600 UT on 30 October, respectively. These storms have been investigated from the perspective of the effect they produced in the ionosphere-thermosphere systems at different latitude regions. For some of the response features over equatorial, low, and middle latitudes, see, for example, *S. Basu et al.* [2005], *Su. Basu et al.* [2005], *Batista et al.* [2006], *Foster et al.* [2005], *Lin et al.* [2005a, 2005b], *Sahai et al.* [2005], and *Zhao et al.* [2005]. We will present in this paper the equatorial and low-to-middle latitude ionospheric responses to the storms of 29 and 30 October over two widely separated longitudes: the Brazilian sector around 45°W longitude and the Japanese-Asian sector that covers a longitude range 105°–130°E, with them being separated in local time by 10.5–12 h. We will be analyzing the following ionospheric parameters: the *F* layer heights at different plasma frequencies and the hmF2, the peak density represented by the foF2 and the vertical drift as measured by ionosondes/digisondes, the total electron content (TEC) as obtained from a GPS receiver network, and the electrojet intensity represented by the horizontal magnetic field variations in equatorial magnetograms. We will be discussing in some detail the ionospheric effects in terms of the equatorial ionization anomaly development/suppression processes in response to disturbance electric fields and disturbance meridional winds of episodic nature as a function of the storm phases and their local time/longitude dependences. For the first time we will present evidence of nighttime westward electrojet current driven by a PP westward electric field. Observational evidences on the longitude dependence of the prompt penetration electric field (PPE) and disturbance wind dynamo electric (DDE) will be discussed [see also *Abdu et al.*, 1995] in the light of their recent model predictions [*Richmond et al.*, 2003] and to understand the relationship, if any, between the nature of the equatorial anomaly disturbance features observed in the two widely separated longitude sectors. We will examine such phenomenological responses with the help of the interplanetary magnetic field component *Bz* as measured by the ACE satellite at the L1 point, the auroral electrojet *AE* activity index calculated from 65 stations between latitudes 52.9° and 76.3° [*Zhao et al.*, 2005] and the Sym-H index (as published by the World Data Center, Kyoto) used as proxy for the *Dst*, and magnetic field *H* component from Yap and Guam stations in the Pacific. *Fejer and Scherliess* [1997] have pointed out that the *AE* activity is an important, but not sufficient, control parameter to describe the equatorial disturbance electric field. The *AE* fluctuations during these storms were of much extended durations and of large amplitudes, and hence the response features to be discussed are generally quite complex. Our approach is to focus on specific response features attempting to connect them to *AE*/*Bz* variations through associated disturbance electric fields and inferred wind disturbances. The discussions will be based on the theoretical expectations and recently available model results.

2. Observational Data Sets From Brazilian and Asian Sectors

[5] Ionosphere sounding data registered by digisondes from three stations (São Luís, SL; Fortaleza, Fz; and Cachoeira Paulista, CP) having latitudinal coverage from close to magnetic equator to the equatorial anomaly crest location are used from the Brazilian sector. In the Japanese-Asian sector data from the meridional chain of four ion-

Table 1. Coordinates of the Stations Used in the Analysis

Station	Geographic Longitude	Geographic Latitude	Magnetic Dip Angle
São Luís	44.2°W	2.33°S	∼2°
Fortaleza	38.45°W	3.9°S	−9°
Cachoeira Paulista	315°E	22.6°S	−34°
Chumphon	99.38°E	10.72°N	6.0
Okinawa	128.16°E	26.68°N	37.8°
Yamagawa	130.62°E	31.20°N	44.5°
Kokubunji	139.49°E	35.71°N	49.3°
Kakkanai	141.69°N	45.39°N	59.8°
Yap	138.5°E	9.3°N	3.0°
Guam	144.87°E	13.58°	12.1°

osonde stations in Japan (Okinawa, OKI; Yamagawa, YAM; Kokubunji, KOK; and Wakkanai, WAK) and an equatorial station in Thailand (Chumphon, CPN) are used together with the TEC data collected from the dense Japanese GPS receiver network, GEONET. Magnetometer data from the Pacific electrojet region stations (Yap and Guam) are also used to complement the study. The coordinates of these stations are given in Table 1. The ionosonde/digisonde data were taken at 15-min resolution (except for Fz where 10-min data were available). The magnetic data have 1-min resolution. For the GPS TEC data, see the specifications given by *Maruyama et al.* [2004].

3. Interplanetary and Geomagnetic Disturbance Conditions

[6] The interplanetary magnetic field component *Bz*, the auroral electrojet activity index *AE*, the *Dst* index, and the *d*(*Dst*)/*dt* parameter, all at 1-min resolution, are presented in Figure 1. A sudden southward turning of the *Bz* at 0610 UT on 29 October accompanied by a storm sudden commencement marked the storm onset seen as large intensification of the *AE* followed by its recovery and renewed activity that lasted till ∼1300 UT during which the storm growth and partial recovery characterized the *Dst* variations. New intensifications in both the *AE* and *Dst* activity soon began at ∼1500 UT of the same day, and large amplitude *AE* fluctuations with simultaneous *Dst* decrease and partial recovery, with superposed transient *Dst* variation, continued till ∼0300 UT of 30 October. The recovery of this second storm event seems to have lasted till around 1600 UT of the same day. A major *AE* intensification that started at ∼1630 UT (of 30 October) was accompanied by a small *Dst* decrease till ∼2000 UT. A larger *AE* intensification of comparable magnitude as the first one (of 0610 UT of 29 October) but with a two-stage development phase started at ∼1830 UT that was followed by a series of *AE* intensification/recovery episodes that lasted till ∼1400 UT of the 31 October. The rapid *Dst* decrease that set in by 2000 UT continued till 2300 UT of 30 October, after which the recovery phase continued beyond 1400 UT of 31 October. A series of *Dst* fluctuations were superposed on this recovery phase, while small amplitude *AE* activity persisted till the end of 31 October. The *d*(*Dst*)/*dt* parameter (representing the *Dst* change per minute) that was obtained from the *Dst* values at 2-min running interval shows often large amplitudes in association with the *AE* intensifications. It is important to note that there are significant exceptions to such association, however. It may be mentioned that a large part of the ionospheric response characteristics will be examined in the light of PPE of undershielding/overshielding conditions corresponding to *AE* development/recovery phases.

4. Major Ionospheric Response Features

4.1. Brazilian Longitude Sector

[7] During the first of the shock events, which was marked by an abrupt southward turning of the IMF *Bz* at

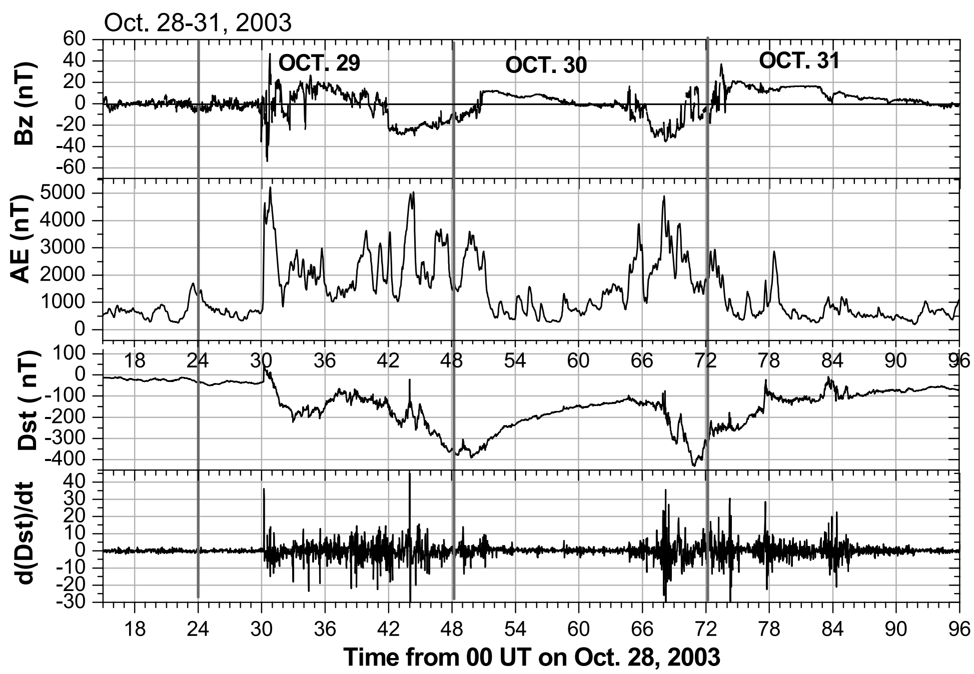

Figure 1. One-minute plots of (first panel) the IMF *Bz*, (second panel) the *AE* index, (third panel) the Sym-H which is equivalent to the *Dst*, and (fourth panel) *d*(*Dst*)/*dt*.

0610 UT of 29 October the storm sudden commencement, as indicated by a sudden increase of *Dst*, occurred nearly simultaneously with the onset of an auroral substorm marked by an *AE* intensification of ~4500 nT as can be noted in Figure 1. Figure 2 shows 1-min plot of the *AE* index (first panel), the *F* layer peak height (hmF2) and the true heights at specific plasma frequencies at 1 MHz interval starting at 3 MHz and up (third panel), and the foF2, representing the peak density of the layer (NmF2) (bottom panel) as obtained by a Digisonde 256 [*Reinisch et al.*, 1989] at São Luís. Similar results for Fortaleza in Figure 3 and for Cachoeira Paulista in Figure 4 were obtained by a DPS-4 (Digital Portable Sounder) and a digisonde, respectively. The immediate response of the *F* layer parameters to the SSC and substorm onset at 0610 UT is seen as a rapid decrease in the *F* layer heights clearly observed over SL and Fz but less clearly over CP. This rapid decrease is a response to an undershielding PPE of westward polarity. *Batista et al.* [2006] have determined for this case the downward drift velocity, using the Sheffield University Plasmasphere-Ionosphere Model (SUPIM) [*Bailey et al.*, 1993], to be ~130 m s^{-1}, which corresponds to a westward electric field of ~3 mV m^{-1}. (We may note that the apparent downward drift velocity as obtained by the rate of the height descent (*dh*/*dt*) was only 41 m s^{-1}, in this case.) Prompt penetration westward electric field of 4.5 mV m^{-1}, in response to the great magnetic storm of July 2000, has been observed in the midnight sector over India by *Sastri et al.* [2002]. The downward velocity over Fz appears to be smaller than over SL which seems to due to the effect of plasma uplift by the nighttime equatorward background wind [*Pincheira et al.*, 2002] being larger over Fz (see Table 1). The same wind seems to be responsible for a significant cancellation of the downward drift over CP where the larger magnetic inclination could cause larger wind induced plasma uplift.

[8] The rapid layer descent to lower heights of increasing recombination resulted in large decrease in foF2 approaching the lower limit of the ionosonde detection, clearly noticeable at SL and Fz (the concurrent foF2 decrease over CP appears to have additional causes). The *AE* recovery phase that followed the 0610 UT intensification was associated with the *Bz* turning northward (Figure 1). Here the effect of an overshielding eastward electric field can be noted in the form of a tendency for the *F* layer height to increase (soon interrupted in the data due to a depleting ionosphere over SL and Fz, Figures 2 and 3). The associated eastward electric field appears to be responsible, through fountain effect, for the development of equatorial anomaly in the morning hours as indicated by a large increase of foF2 (reaching ~18 MHz) over CP at ~0930 UT/0630 LT (see Figure 4). This event was the focus of a recent paper by *Batista et al.* [2006] and will not be discussed here further.

[9] The ensuing height variations in response to the *AE* intensification episodes present a complicated cause-effect relationship. While the photochemistry of the daytime could mask the hmF2 response to disturbance electric fields, the generally larger hmF2 in the afternoon hours of 29 and 30 October could be an indication that the long-duration high-intensity *AE* activity that prevailed at these hours might have caused a PPE under imperfect shielding conditions dominating any DDE westward electric field that is expected to be present at these hours (for some cases of long-duration PPE [see, e.g., *Huang et al.*, 2005]). Approaching the evening hours the height response to specific *AE* intensification episodes gets better defined. It is interesting to note that a minor *AE* intensification that occurred right at 1800 LT (2100 UT) of 29 October, in-phase with the evening prereversal electric field enhancement (PRE) appears to be responsible for the larger vertical drift/layer uplift on this evening as compared to the previous evening (Figure 2) [*Abdu et al.*, 2003]. This enhanced vertical drift promptly caused postsunset spread *F* irregularity generation (marked by horizontal bars) that was restricted to the equatorial latitudes only (Figure 2) as can be verified from its late start time over Fz (Figure 3) and its absence till midnight over CP (Figure 4). Here we note a possible influence of a transequatorial wind (northward in this case) to suppress the plasma bubble development [*Maruyama*, 1988; see also *Abdu et al.*, 2006a]. We further note that a ~1900 UT (1600 LT) *AE* intensification episode has caused EIA enhancement as can be verified from the subsequent increase of foF2 over CP (starting near 2000 UT) accompanied by its decreases over SL and Fz with respect to the reference day.

[10] The next prominent ionospheric disturbance phase started with nearly simultaneous and large height increases during the postmidnight hours (of 29–30 October) over the three Brazilian stations. This appears to be a response to a DDE that has eastward polarity at these local times [*Richmond et al.*, 2003]. The mean vertical drift velocities during a common time interval at the three sites SL, Fz, and CP come out to be 25, 14, and 15 m s^{-1}, respectively. The larger height fluctuations over CP and they being not in-phase at the three sites would suggest the presence of a fluctuating meridional winds during these hours. As indicated by the foF2 variations over CP the EIA intensity appear to be fluctuating under the action of the eastward DDE and disturbance meridional winds. With the sunrise the DDE turns westward which seems to have caused an inhibition of the EIA till afternoon hours of 30 October, as indicated by the lower than (larger than) normal foF2 values over CP (SL and Fz) (Figures 2, 3, and 4).

[11] On 30 October the oscillatory variations in *Bz* that started at ~1600 UT was accompanied by intense *AE* activity which seems to have produced the PP electric fields responsible for the episodic enhancements of the *F* layer height over SL identified as 3, 4, and 5 in Figure 2. The corresponding height fluctuations over Fz and CP seem to have been suppressed possibly by a fluctuating disturbance meridional wind. The most intense of the layer uplift that occurred at sunset (identified as 6 in Figure 2) corresponds to a vertical drift velocity that was >700 m s^{-1} as estimated from the height increases of the *F* layer trace in the successive ionograms taken at 15-min interval. The vertical velocity as determined from the back-scatter echoes observed by a 30-MHz VHF radar at São Luís was of the order of 1200 m s^{-1}. This is the largest vertical drift ever recorded by radio sounding technique of the equatorial ionosphere so far. This appears to have been caused by an intense eastward PPE associated with a severe and rapid *AE* intensification (by ~2000 nT) that occurred right at ~2100 UT (1800 LT) which coincided with the maximum of the evening prereversal enhancement in the eastward electric field. The spread *F* irregularities that

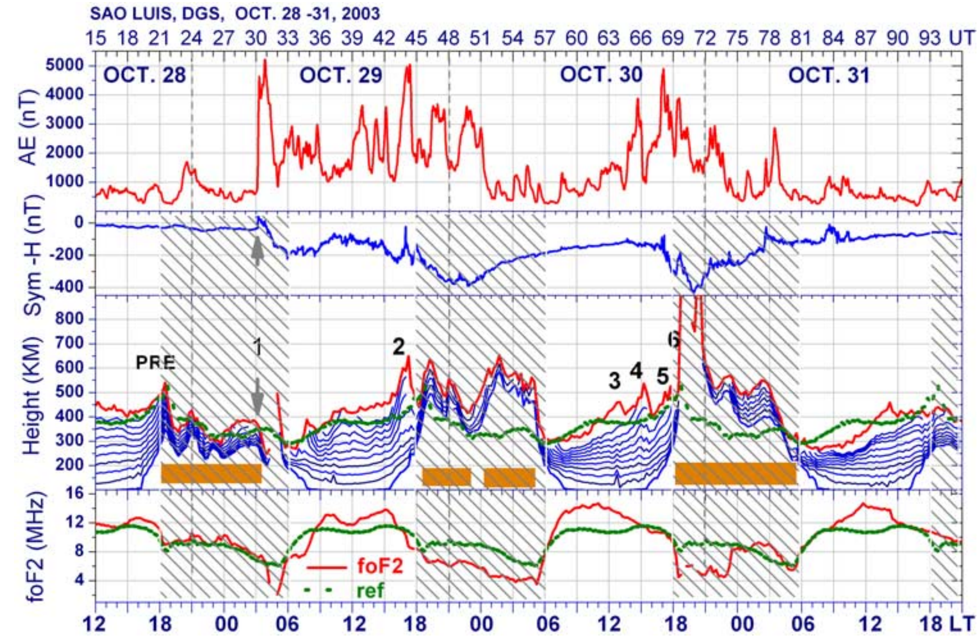

Figure 2. One-minute (first panel) *AE* and (second panel) *Dst* (Sym-H) plots during the storm events from 1500 UT of 28 October until the end of 31 October; *F* layer true heights at specific plasma frequencies at 1 MHz interval starting at 3 MHz and upward (blue curves), together with the hmF2 values (red curve). (third panel) A reference hmF2 curve representing the mean of a few quiet days (olive curve); and (fourth panel) *F* layer peak density represented by foF2 (red curve) and its reference day curve (olive curve). The height increase near 1800 LT (2100 UT) that is repeated every day on the quiet day curve is due to the prereversal enhancement of the zonal electric field (PRE). The UT hours are counted from the 0000 UT of 28 October 2003. (The marks of 24, 48 and 72 UT indicate the 0000 UT of the successive days.) Local night hours are indicated by grey hatched areas.

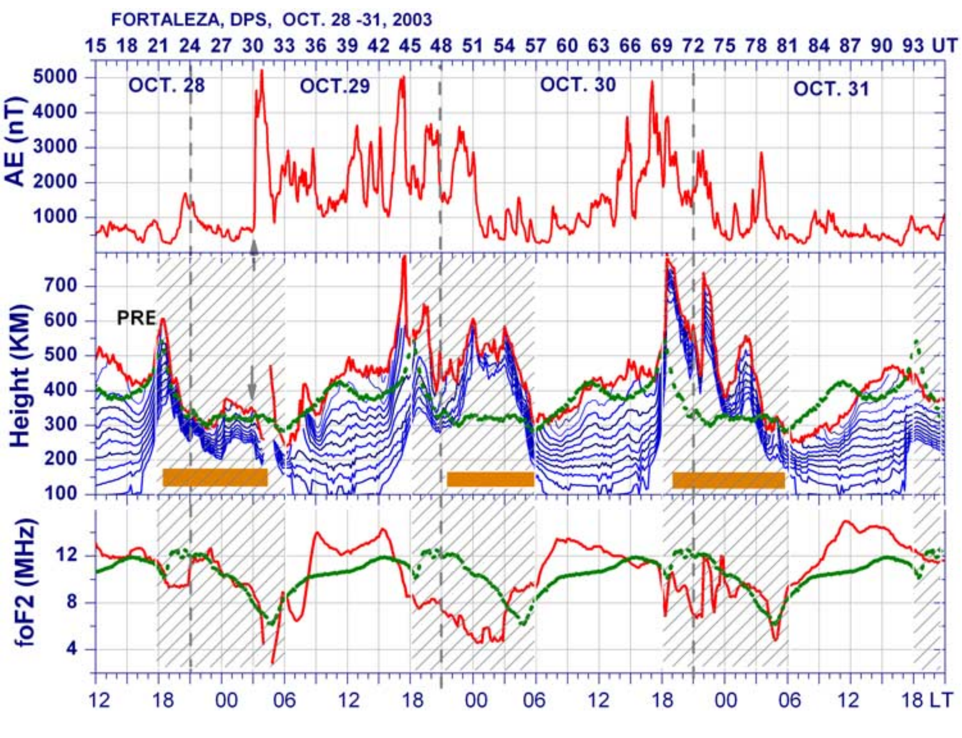

Figure 3. Plots similar to those of Figure 2 but for Fortaleza, without the *Dst* (Sym-H) plot.

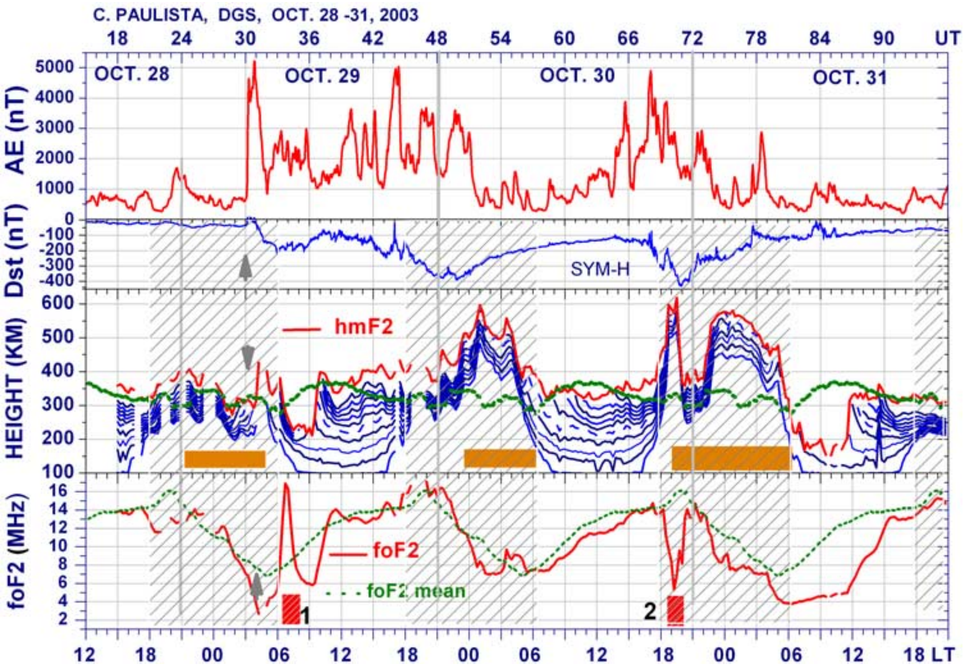

Figure 4. Plots similar to those of Figure 2, but for Cachoeira Paulista.

developed on this evening were not particularly more intense as compared to its normal intensity (these aspects will be published elsewhere). The vertical drifts over Fz and CP were progressively smaller than that over SL suggesting the presence of an intense disturbance poleward wind at this time. The nature of the height fluctuations at the three locations after about midnight (extending to the presunrise hours) would suggest the role of a DDE that maintained the *F* layer above the quiet time level (as observed on the previous night as well), but with certain fluctuating intensity (as indicated by the height oscillations over SL). The larger height increases/fluctuations around midnight over Fz (Figure 3) and CP (Figure 4), as compared to SL, seem to suggest strong equatorward wind surges that followed the earlier intense poleward wind (mentioned above). With sunrise the polarity of the DD electric field turned westward causing descent of the *F* layer below the quiet time levels over all the three stations in the morning of 31 October. The layer height decrease was more pronounced over Fortaleza than over SL and spectacularly below normal over Cachoeira Paulista (Figure 4) where the hmF2 descended to heights below 180 km, and as a results of the recombination loss of plasma the foF2 was reduced to significantly lower values as compared to its quiet time reference. This feature of the hmF2 descent over CP indicates the presence of strong poleward disturbance wind during these morning hours. (At the same UT when it was evening over Japan strong equatorward disturbance wind of approximately the same duration was observed as will be discussed in sections 4.2.2 and 5.4.) The role of a poleward wind to cause large decrease of hmF2 has been demonstrated from analysis of storm response over Arecibo by *Buonsanto and Foster* [1993]. This poleward wind over Brazil seems to have lasted till midday when the hmF2 over CP abruptly recovered to its normal values. The rapid recovery of the *F* layer peak height, apparently driven by a reversal of the wind to equatorward, produced a slower recovery of the foF2, which appear to suggest that the EIA response time to a changing wind could be of the order of 3 h, confirming previous finding by *Abdu et al.* [1990]. (An exactly opposite variation in foF2 was observed simultaneously in the Japanese sector which is discussed in sections 4.2.2 and 5.4.) The background westward DDE seems to have prevailed till at least the evening hours as indicated by the near inhibition of the evening prereversal *F* layer uplift over both SL and Fz. Some of these response features in the American longitude sector have interesting counterparts as well as other distinctive features over the Japanese-Asian longitude sector as we discuss in sections 4.2.2 and 5.4.

4.2. Japanese-Asian Longitude Sector

4.2.1. Equatorial Sites

[12] The initial SSC event and *AE* intensification at 0610 UT (of 29 October) occurred during the afternoon hours in the Japanese-Asian longitude sector. The magnetic field *H* component variation due to the EEJ over Yap was obtained by subtracting from the *H* variation over Yap the corresponding *H* component variation over an off-EEJ station, Guam. The variation of this parameter, ΔH(Y-G), during the 28–31 October interval is plotted Figure 5 together with the *F* layer virtual heights at specific plasma frequencies (4, 5, 6, 7, and 8 MHz) and the foF2 over Chumphon (close to the dip equator, see Table 1). (The LTs of Yap and CPN are 9.2 h and 7 h ahead of UT, respectively.) The storm onset was at 1530 LT over Yap where the *H* component due to the quiet day EEJ (shown by the reference curve) was well into its afternoon decay phase. With the SSC and the *AE* increase at 0610 UT a sudden increase in the EEJ intensity by 25–30 nT (highlighted by an arrow) suggested the presence of a prompt penetrating eastward electric field. This increase is significantly smaller than that registered over Yap during an intense

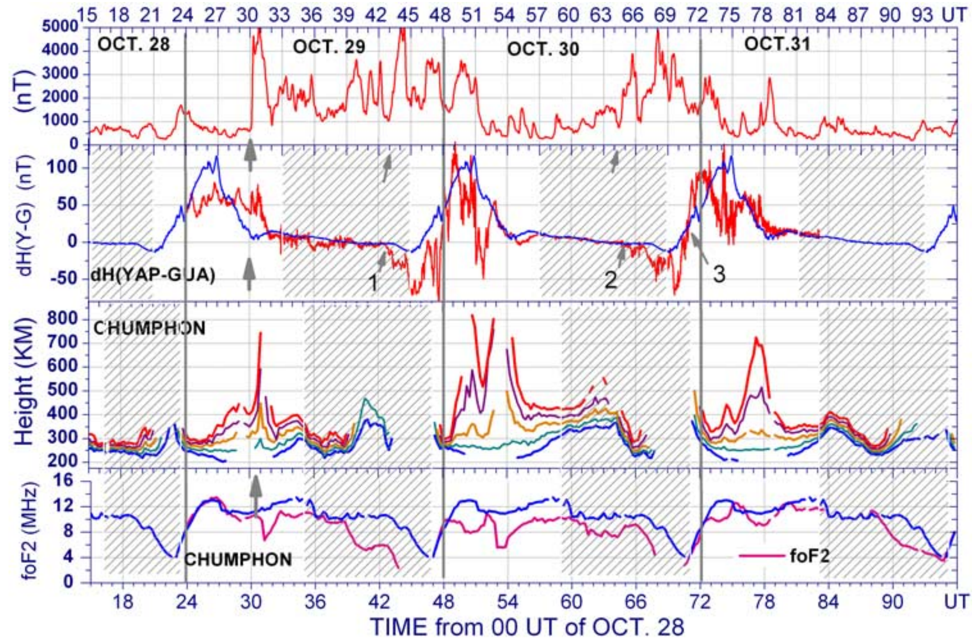

Figure 5. (first panel) *AE* index. (second panel) The magnetic field *H* component variations due to the EEJ over Yap are obtained as explained in the text with a reference/quiet day (smoothly varying) curve; (third panel) the virtual height of the *F* layer at the plasma frequencies, 4, 5, 6, 7, and 8 MHz over Chumphon (CPN); and (fourth panel) foF2 over CPN. Night hours are indicated by grey hatched areas.

storm of 6 November 2001 that was 160 nT, for which the causative *AE* intensification was of somewhat smaller amplitude [*Tsurutani et al.*, 2004] and occurred at ∼1140 LT. The reduced intensity of the response in the present storm can be attributed mainly to the decaying conductivity of the postnoon ionosphere. Further, the magnetic local time dependence of the undershielding (partially shielded) PPE intensity at equatorial latitudes as modeled by *Richmond et al.* [2003] predicts a lower intensity at this local time (1600 LT) compared to that of noon. At Chumphon where the LT is ∼2 h behind Yap, the PP eastward electric field appears to be stronger as seen in the ''large'' increase in the virtual heights at all the higher plasma frequency values (6, 7, 8 MHz) (Figure 5, third panel). The foF2 (Figure 5, fourth panel) shows a sharp decrease at 0700 UT approximately coinciding with the height increase. A strong equatorial plasma fountain caused by the PP electric field can be responsible for this foF2 decrease. The vertical velocity, based on the virtual height rise at 7 MHz estimated as $d(h'F)/dt$ is 66 m s^{-1}. It should be pointed out, however, that this velocity can be subject to some uncertainty due to the use of virtual heights for its calculation (and possible effect from the daytime photochemistry of the ion production process). The *F* layer heights near sunset seems to have suffered a decrease with respect to the values on the evening of 31 October in Figure 5 (that can be considered as a reference) indicating the presence of a westward DDE. The electric field seems to have turned eastward just before midnight as indicated by an increase in the *F* layer height and a decrease in the foF2 over CPN. Competing influences of an *AE* intensification at ∼1500 UT and an expected midnight turn over to eastward of a DDE electric field [*Richmond et al.*, 2003] must be influencing this changes.

[13] A more intense *AE* enhancement at ∼1900 UT/ 0400 LT (on 29 October) caused a sudden development of a westward electrojet seen as a negative deviation in the $\Delta H(Y - G)$, which is identified as 1 in Figure 5. The initial amplitude of the ΔH was ∼30 nT. This was caused by the westward phase of the global dawn-dusk electric field (associated with the 1900 UT *AE* enhancement) that penetrated to low latitude. The same westward electric field seems to be responsible for maintaining downward the *F* layer over CPN and the foF2 further decreased under recombination process (to below the sensitivity limit of the ionosonde). This situation resulted in the absence of data for a few hours during which a westward electric field appears to have prevailed for much of the time as can be verified from the $\Delta H(Y - G)$ plot. It is interesting to observe that the EEJ westward current showed a rapid increase (reaching about −70 nT) with the increase in the *E* layer conductivity at sunrise. (A small and very short duration decrease in the westward EEJ current just before 0600 LT appears to be in response to the *AE* decrease phase that followed its 1900 LT intensification. Fluctuations in the EEJ intensity seems to be superposed on a background daytime westward DDE and seems to follow the phases of the large *AE* fluctuations. In particular, a large *AE* recovery that occurred during 0300–0400 UT (1200–1300 LT) has produced a large westward EEJ at this local time. The *F* layer height oscillations over CPN also shows clear indication of the presence of a strong westward electric field at this time when a depression of the *F* layer height (from its abnormally large values) centered at 0300–0400 UT, is evident. The foF2 shows variation over CPN in approximately antiphase with the height variations as to be expected near the equator. The large height oscillations (0100–0700 UT) indicate also oscillations in the layer thickness accompanied by antiphase oscillations in

foF2. The presence of a westward DDE into the sunset hours is indicated by the reduced amplitude of the PRE (as judged by the near zero value of the $d(h'F)/dt$ at these hours).

[14] On the night of 30 October a large *AE* intensification that set in at 1630 UT again produced response in the nighttime EEJ over YAP and in the *F* layer height and foF2 over CPN, very similar to the effects observed on the previous night (that was associated with the 1900 UT onset of *AE* intensification of 29 October, Figure 5). The development of westward EEJ and its intensification in antiphase with the intensifications in *AE* can be noted till sunrise (on 31 October). However, an intensification of the westward EEJ did not occur right at sunrise as happened on the previous day, instead an *AE* intensification that occurred at this time (2100 UT/0600 LT), followed by immediate partial recovery, seems to have delayed the process of the westward EEJ intensification due to sunrise. (We should note here that the PPE polarity at this time of night-to-day transition to be associated with an *AE* intensification is one of being close to the transition from negative to positive sense as per the model results of *Richmond et al.* [2003], and hence the identification of the response feature at this time is subject to some uncertainty.) Over CPN the predominantly westward electric field episodes produced significant descent of the *F* layer and the disappearance of the ionogram trace for a few hours until sunrise, as occurred on the previous day (Figure 5). While the rapid increase to eastward EEJ during 2200–2400 UT (0700–0900 LT) could be related to the *AE* recovery that occurred at this time the subsequent EEJ variations appear related to the *AE* fluctuation in rather complex ways.

4.2.2. Low-Latitude to Midlatitude Sites

[15] The deviation in the hmF2 and foF2 with respect to their respective reference curves were calculated for the four Japanese stations, Okinawa, Yamagawa, Kokubunji, and Wakkanai. The set of quiet days used for the reference curves in all the cases is the same as that used for Brazilian data. The results of ΔhmF2 during the period from 1500 UT of 28 October (0000 LT of 29 October) to 0000 UT (0900 LT) of 1 November 2003 are presented in Figure 6a. The eastward PPE that produced significant *F* layer height increase over the equatorial site CPN corresponding to the 0610 UT start of the substorm on 29 October seems to have caused only some very minor positive height deviations over Okinawa and Yamagawa (1510 LT) with no indications of its presence further northward. This weak/ambiguous height response is similar to the height response over Cachoeira Paulista on the nightside (Figure 4) but expected to be in opposite sense. A second increase in the *AE* activity that started at ~0800 UT has produced height increase over CPN (Figure 5) as well as over Okinawa and Yamagawa where it seems to be better defined than for the first (0610 UT) episode. (There is indication that corresponding response in the *F* layer height over Brazil is in opposite sense.) However, the positive height deviations increasing toward higher latitudes (Figure 6a), with some time advance, clearly seen in this case would suggest the dominant role of an equatorward propagating wind surge that seems to have modulated whatever height increase due to PPE that was present at the two lower-latitude stations. The responses in the foF2 at the four ionosonde stations are presented in the form of ΔfoF2 in Figure 6b. We note increase of foF2 at 0700 and 0900 UT over Okinawa and Yamagawa (somewhat clearly) which can be attributed to EIA enhancement due to the eastward PPE associated with the above mentioned two *AE* intensification episodes.

[16] The latitude versus UT distribution of the deviation in TEC (ΔTEC) as obtained from the dense Japanese GPS station network is presented in Figure 7. Two different types of TEC enhancement are easily distinguishable in these plots. The TEC enhancement (colored in orange) at 0000–0200 UT on 29 October is simultaneous at wide latitudes, while that at 0200–0500 UT on the same day shifts to later times at lower latitudes. The former is attributed to an eastward PPE and the latter corresponds to an equatorward wind surge. The delayed enhancement at higher latitudes seen at around 0900 UT on 30 October is discussed by *Maruyama et al.* [2004]. We note that ΔTEC variations in general follow that of ΔfoF2, especially at lower latitudes (with some exceptions to be pointed out below). Thus, following the 0610 UT storm onset, an EIA enhancement in the TEC and foF2 is clearly seen extending from Okinawa to Wakkanai. We note further that the anomaly enhancement that followed the second *AE* episode (starting at 0800 UT) also extended from Okinawa to Wakkanai with ~1 h time delay (with respect to the hmF2 enhancement) and displayed a delayed enhancement at higher latitudes similar to the case at 0900 UT on 30 October, just mentioned above.

[17] The *AE* decrease near 1200 UT (on 29 October) appears to have produced a decrease of *F* layer height over CPN (Figure 5) due to a PP electric field of westward polarity expected of an overshielding electric field at this local time. However, over the Japanese ionosonde stations that are ahead in local time by ~2 h the *F* layer presented large uplift (at 2100 LT, Figure 6a) as if due to an overshielding eastward electric field, and in the presence of an equatorward disturbance wind. Correspondingly the foF2 variation showed sharp depression at all the stations (Figure 6b). The next *AE* intensification that occurred at ~1500 UT/2200 LT (of 29 October) might have influenced the height changes over CPN (as mentioned before) and the Japanese stations. However, the large but slowly rising positive ΔhmF2 over OKI and YAM (soon after 1500 UT) appears to be due to an eastward DDE with possible influence of an equatorward disturbance wind. (The effects over the other stations, if any, appear masked by overwhelming influence of disturbance winds prevailing at these times.) Both the ΔTEC (Figure 7) and ΔfoF2 (Figure 6b) indicated EIA enhancement at lower latitudes, correspondingly. While the hmF2 increase arising from a predominantly eastward electric field causes increases in foF2 and TEC as is apparent in this case, the hmF2 increases arising predominantly from the influence of an equatorward wind may not cause such increase of foF2 and TEC under nighttime conditions (as will be seen below).

[18] The major *AE* intensification at ~1900 UT (29 October) that caused the development of westward EEJ current over Yap, and *F* layer descent over CPN, under a westward PPE (mentioned before) was also responsible for a significant *F* layer descent over all the Japanese ionosonde stations (Figure 6a). This negative ΔhmF2 seems to be associated with a decrease of ΔfoF2 (from its elevated

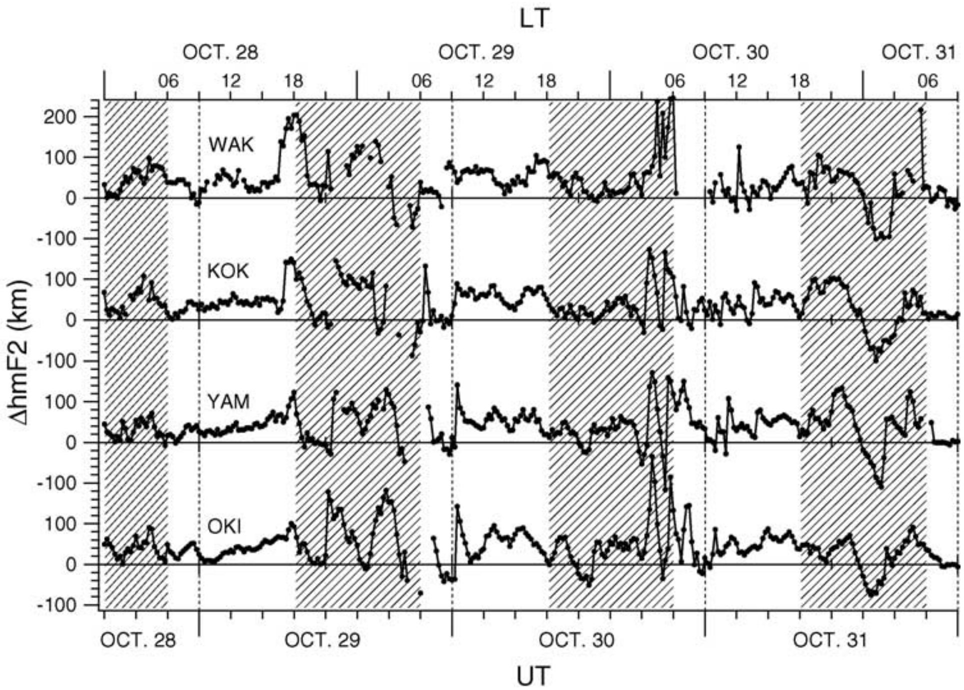

Figure 6a. *F* layer peak height hmF2 deviation form its reference day curve, ΔhmF2, during the period from 1500 UT of 28 October (0000 LT of 29 October) to 0000 UT (0900 LT) of 1 November 2003. The ΔhmF2 variations are shown from bottom to top for Okinawa, Yamagawa, Kokubunji, and Wakkanai. The shaded areas represent the local night hours.

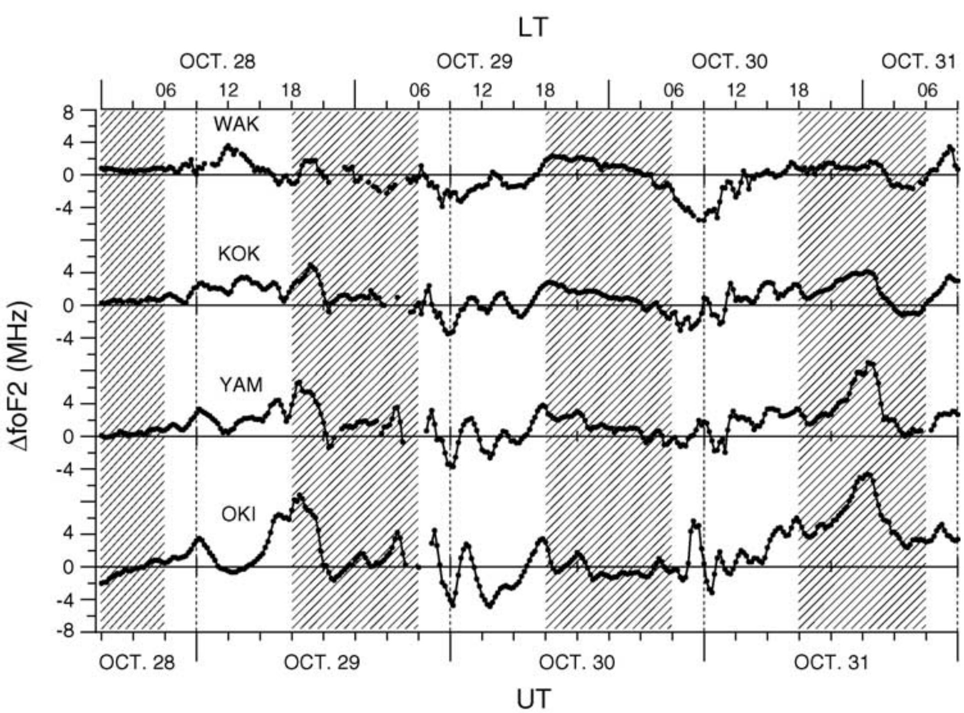

Figure 6b. Similar to Figure 6a, but for the parameter foF2.

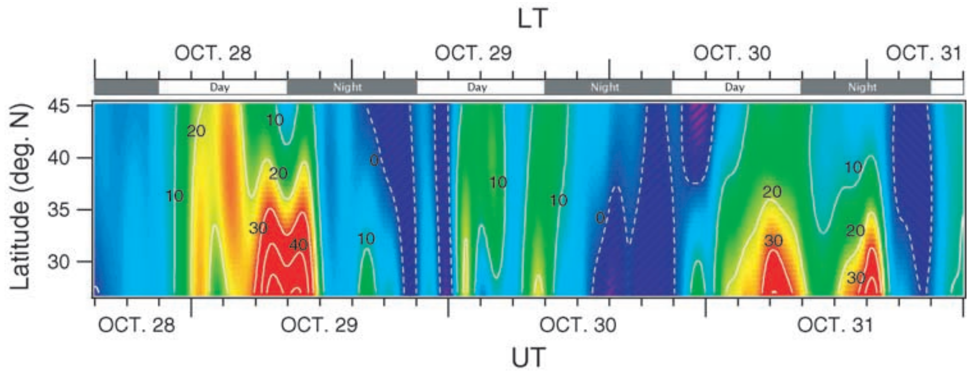

Figure 7. TEC deviation with respect to a reference day (quiet days mean) plotted in latitude versus UT format for the dense GPS receiving station network in Japan, during the same period as that of the other figures. Blue color with slashes indicates negative ΔTEC and red color indicates maximum positive ΔTEC.

values over lower latitudes) suggesting an EIA inhibition (although data break does not permit a clear definition of the negative foF2 deviation) which is clearly evident also from the negative ΔTEC values at ~2000 UT/0500 LT. The response feature for the case of the *AE* intensification that occurred at 2200 UT appears to be a reduction on the westward EEJ over Yap presumably by an eastward PPE. The ΔhmF2 response over Japanese stations is not clear, apparently due to the influence of an equatorward wind surge. The increase in ΔfoF2 involving some time delay toward lower latitude (accompanied by positive ΔTEC at all latitudes) would suggest an EIA enhancement near 2200 UT/0700 LT, however. The disturbance wind appears to have decreased in intensity or turned poleward (especially at lower latitudes) which apparently resulted in the ΔfoF2 and ΔTEC decreases near 0000 UT/0900 LT.

[19] A rapid increase of ΔhmF2 at lower latitudes on 30 October in Japan (Figure 6a) soon after 0000 UT (0900 LT) was followed by increase in ΔfoF2 (Figure 6b) which indicated an EIA enhancement. A sudden eastward increase of EEJ over Yap (at 0000 UT, Figure 5) that accompanied this episode (the *F* layer heights over CPN not responding due to the sunrise transition) would suggest an eastward PPE as the cause of this EIA enhancement. Here the source of the electric field is most likely an *AE* recovery phase, and hence an overshielding eastward electric field. We may point out here that the eastward polarity of an overshielding electric field at 0900 LT does not look to be in agreement with the model predictions (such as *Richmond et al.* [2003]).

[20] Further to the effects just described above the dayside responses in the Asian sector on 30 October are very interesting, though complex, especially from the perspective of the latitudinal variation. Large *AE* intensification marked the morning hours with moderate *AE* fluctuations continuing till evening hours in the Asian sector (Figures 1 and 5). The lower than normal foF2 in combination with the large *F* layer uplift over CPN (Figure 5) would suggest that a disturbance plasma fountain whereby plasma was removed from equatorial latitudes was active under an eastward PPE that appears to dominate the daytime. (It should be pointed here that over CPN where the dip angle is 6° the possibility of some degree of influence in the *F* layer height variation due to disturbance winds cannot be ruled out.) This disturbance fountain should have led to EIA development, that is, increase of the foF2 over Japanese stations. We notice, however, dominantly negative ΔfoF2 variation (with some important exceptions) over these stations (notably over Okinawa located close to the quiet time anomaly crest). ΔhmF2 shows significant positive values over these stations suggesting the presence of strong equatorward disturbance winds due to the preceding intensifications in the *AE* activity. The ΔTEC shows positive deviations at these times. Theoretical simulation results by *Lin et al.* [2005b] have shown TEC enhancement at low and middle latitudes as a result of an equatorward disturbance wind partially opposing the plasma descent to higher latitudes that operates as part of the fountain process. The ΔfoF2 deviations at lower latitudes (Okinawa and Yamagawa) are positive during approximately 0100–0200 UT/1000–1100 LT and for a few hours starting from 0700 UT/1600 LT which is reflected also in the ΔTEC variation. However, the ΔTEC variation is neither proportional to, nor in-phase with, the variations in ΔfoF2, as was noted above; see also their out-of-phase deviations over the low latitudes during ~0200–0700 UT/1100–1600 LT of this day. Such variable dependence of the TEC on foF2 has been discussed by *Maruyama et al.* [2004] in connection with the 6 November 2001 storm event. As a result of the equatorward winds (positive hmF2) persisting till evening hours, the TEC enhancement continued into the early night hours (Figure 7). We may note, however, that a negative deviation in hmF2 indicating a poleward reversal of the wind that started near 1100 UT/2000 LT (mainly over lower latitudes, Figure 6a) caused an foF2 increase followed by a decrease that appears to be partially reflected in the TEC variations, but an equatorward reversal of the wind that occurred near 1330 UT/2230 LT (clearly identified over OKI and KOK) did not apparently produce any effect in foF2. The ΔfoF2 and the ΔTEC at most latitude remained negative (or very small) in the following few hours.

[21] The next major *AE* intensification episode starting at ~1630 UT (30 October UT) that produced the *F* layer descent and the disappearance of the ionogram trace over CPN (as explained in section 4.2.1) also caused *F* layer height decrease over OKI to WAK, but apparently influenced by superimposed effects from strong equatorward winds. However, within about an hour the hmF2 did show decrease as to be expected from a westward PPE, which was

soon followed by strong height oscillations (apparently induced both by the PPE associated with the *AE* episodes as well as by superposed winds) that prevailed till sunrise of 31 October (Figure 6a). A rapid increase of *AE* at 2100 UT of 30 October (just around sunrise) that was followed by a two-stage *AE* recovery appears to be associated with the *F* layer uplift over OKI at ~2200 UT/0700 LT. We may attribute this to the overshielding electric field of eastward polarity associated with the 2200 UT *AE* recovery in near agreement with the model results of *Richmond et al.* [2003]. The possible corresponding effects at higher latitudes are confounded by the influence of a disturbance wind. This overshielding eastward electric field caused equatorial anomaly development as can be verified from the positive ΔfoF2/ΔTEC episode peaking around 2300 UT(30 October)/0800 LT(31 October) at lower latitudes over Japan.

[22] Much of the daytime of 31 October in the Asian sector was dominated by eastward electric field similar to the conditions that prevailed on the previous day (Figure 5). This can be verified from the higher than normal *F* layer heights associated with lower than normal foF2 over CPN. The daytime was also marked by equatorward disturbance winds indicated by the positive ΔhmF2 at low to middle latitudes over Japan (Figure 6a) that prevailed during all the day. The TEC presented positive deviation for much of the daytime (except north of 38° latitude in the morning hours) as a results of the persistence of equatorward wind. Additionally the anomaly enhancement on this day appears to be more intense than on the previous day which might most likely be due to the different latitudinal structure of the meridional winds, the contrast with the previous day being more marked in the foF2 values of the afternoon-evening hours.

[23] The positive ΔhmF2 indicating equatorward disturbance winds continued into night hours over OKI to WAK on 31 October. Correspondingly the foF2 also showed larger positive deviations. With the ΔhmF2 starting to decrease by ~1400 UT/2300 LT, at OKI, YAM, KOK, and WAK, indicating a decrease of equatorward wind, the foF2 showed a larger increase over these station, notably over OKI and YAM. The ΔhmF2 subsequently turned negative which suggested a fast descending *F* layer under a poleward wind that maintained a larges ΔfoF2 until past midnight when a sharp decrease in its value set in. This decrease might be the results of the recombination loss of the plasma at the lower *F* layer heights caused by the strong poleward winds. During the phase of equatorward wind the ΔTEC showed large increase similar to the increase in ΔfoF2. It is important to note, however, that the TEC enhancement is relatively more prominent than the ΔfoF2 increase under sunlit condition at lower latitudes. The poleward turning of the wind at ~1500 UT/midnight (as suggested by the hmF2 turning negative) resulted in large decrease of ΔfoF2 as well as significant decrease of TEC, the ΔTEC turning negative during 1800–2100 UT/0300–0600 LT, presenting a delay of 2–3 h with respect to the maximum intensity of the poleward wind. The disturbance winds subsequently turned equatorward, as indicated by the positive ΔhmF2 till past sunrise. It is interesting to note that the increase in ΔhmF2 indicating equatorward winds at 0900 UT/1800 LT, in the evening hours of 31 October over Japan (less conspicuous over OKI) coincides with a strong enhancement in what appears to be a poleward wind over Brazil in the morning hours, as indicated by the sharp decrease of the hmF2 over CP (Figure 4). A dayside depletion in foF2 is present over CP simultaneously with a nightside increase of foF2 over Japan (this point is discussed further in section 5).

5. Discussion

[24] The ionospheric responses to the intense and extended duration storm events of October 2003 as observed in a range of latitudes, extending from the equator to low and middle latitudes, and in two widely separated longitude sectors are indeed complicated. The results presented here concern the response features in the different ionospheric parameters: EEJ intensity, foF2, *F* layer height at different plasma frequencies, hmF2, and TEC. A better understanding of the coupling processes governing these response features can be achieved by discussing/evaluating these results in terms of the disturbance electric fields and winds that exercise latitude-dependent control of these parameters. In the discussion to follow we will focus on the following main aspects: (1) the processes controlling the TEC storm; (2) longitudinal/local time dependences of the disturbance electric fields; (3) equatorial anomaly development by undershielding/overshielding electric fields; and (4) considerations on disturbance winds and dynamo electric field longitudinal distribution/dependence.

5.1. Processes Influencing the TEC Storm

[25] An important aspect of the ionospheric response to magnetic storms concern the large increase in TEC activity known as TEC storm observed mainly on the day and evening sectors [*Abdu*, 1997; *Maruyama et al.*, 2004; *Tsurutani et al.*, 2004; *Lin et al.*, 2005a]. Such TEC storm activity is driven by an equatorward penetrating polar dawn-dusk electric field (prompt penetration electric field) whose eastward polarity produces large uplift of the ionosphere on the dayside and eveningside. The maximum intensity of the TEC storm during the present course of events is significantly weaker over Japan (ΔTEC, ~40 TEC unit, Figure 7) than that was reported for the eastern Pacific sector by *Mannucci et al.* [2005] that was of the order of 180 TEC unit. It is also weaker than that observed by *Maruyama et al.* [2004] in Japanese longitude during the main/development phase of the November 2001 storm that was of the order of 100 TEC unit, although the maximum *Dst* attained during this extended storm event reached higher values (~400 nT) than that was registered during the November 2001 event (~320 nT). An important reason for such difference in the Japanese sector is obviously the local time dependence in the efficiency and polarity of the prompt penetration electric field. The two most intense *Dst* maxima of this entire event sequence occurred when it was morning over Japan, and therefore corresponded to relatively lower efficiency for the prompt penetration of polar electric field [*Richmond et al.*, 2003]. The initial storm onset marked by the largest *AE* intensification (~5000 nT, see Figure 1) occurred when it was afternoon in the Japanese-Asian sector (see Figure 5) that was followed by *Dst* decrease of only ~200 nT. The resulting TEC storm was weak due to the weaker efficiency of the electric field penetration in the afternoon hours

[*Richmond et al.*, 2003] accompanied also by the relatively smaller *Dst* decrease.

[26] Another important factor affecting the intensity of the TEC storm appears to be the intensity and direction of the disturbance meridional winds originating from the auroral Joule heating (and possibly from the neutral acceleration by ion convection under large high-latitude electric fields). An equatorward wind lifts up the *F* layer over middle and low latitudes thereby decreasing the chemical recombination loss of the plasma when, under daytime, ionization production by solar radiation continue at lower heights, the TEC increasing as a results. The foF2 variations are expected to reflect the variations in the TEC, when the topside ionization distribution is in diffusive equilibrium. However, under an imposed disturbance electric field and/or a disturbance meridional wind (especially an equatorward wind) the variations in the two parameters are often neither proportional nor in-phase as the instances in the present results show. As an example, at around 0300 UT on 29 October at Okinawa, ΔfoF2 turned negative but ΔTEC remained substantially positive. Another example is 0000–0900 UT period on 30 October; ΔTEC is positive by >10 TEC units but ΔfoF2 shows mostly negative value. *Maruyama et al.* [2004] have discussed such relationships in connection with the TEC storm event of November 2001. The rapid uplift of the *F* layer due to a prompt penetration eastward electric field causes the density distribution to depart from diffusive equilibrium. On the topside ionosphere the equilibrium tends to be reestablished by an upward field-aligned plasma flux driven by an enhanced diffusion and reduced recombination rates. At the F2 peak, enhancement of the foF2 can take place at a timescale which could vary from 10^3 s at 250 km to 10^4 s at 350 km depending upon the recombination rate [*Maruyama et al.*, 2004]. However, the degree of the eventual foF2 increase could be significantly reduced under an enhanced upward field-aligned plasma flux. Further, an equatorward disturbance wind could cause additional field-aligned upward plasma transport thereby contributing to the increase of topside plasma content and hence the TEC, at the same time causing a slower increase or even a decrease in foF2 as observed in the results over Japan presented in Figures 6a, 6b, and 7 (see especially their variations during the daytime of 30 October). A clear example of foF2 decrease accompanied by TEC and hmF2 increases can be noted on the dayside of 30 October over WAK. In Figure 7 we observe larger positive ΔTEC values occurring mainly during daytime extending into postsunset hours on all the three days. Although some of the ΔhmF2 increase episodes are caused by specific eastward PPE events, the generally positive ΔhmF2 values indicate presence of equatorward disturbance winds in general. Thus we have the situation of ΔTEC enhancements during much of the daytime extending into postsunset hours arising from disturbance eastward electric field as well as from disturbance equatorward winds.

[27] Specific instances of rapid increases in ΔhmF2 arising from PP eastward electric field, in conjunction with possible wind induced response of this parameter, modifying the TEC in different degrees under day and night conditions can also be noted. For example, as pointed out earlier, the *AE* recovery just around 0000 UT on 30 October appear to contribute to the hmF2 increases near 0900 LT (Figure 6a) that caused increase in ΔTEC (Figure 7). However, a relatively large increase in ΔhmF2 that occurred near 1800 UT of 30 October (0300 LT of 31 October), apparently caused by an eastward electric field due to a rapid *AE* recovery does not appear to have altered the ongoing negative ΔTEC values. The discussion presented above clearly shows that besides the eastward PPE an equatorward disturbance wind is an important source of the daytime (extending to postsunset hours) TEC increases during a storm [see also *Lin et al.*, 2005b]. Such a process does not appear to be operating during later hours of the night. A poleward wind, on the other hand could leads to an eventual decrease (due to increasing recombination at descending heights) in TEC and foF2, especially under night conditions, as observed on the night of 31 October to 1 November to be discussed below.

[28] An interesting and complementary aspect of the connection among the meridional wind, foF2 and TEC is manifested in their relative variations on the night of 31 October (Figures 6a and 6b). Around 1400 UT/2300 LT the ΔhmF2 started to decrease over the stations OKI to WAK. Correspondingly, an increase in ΔfoF2 can be noted over these stations but more dominantly over OKI and YAM till ~1600 UT/0100 LT. This foF2 increase seems to be the result of a decreased equatorward wind causing reduced field-aligned upward plasma flux that in turn causing a net plasma accumulation at the *F* layer peak. The ΔhmF2 soon becomes negative indicating reversal of the wind to poleward which causes the field-aligned plasma flow to be directed downward lowering thereby the height of the *F* layer peak considerably. The enhanced recombination loss of the plasma at the lower heights caused the large decrease of ΔfoF2 that followed. The postsunset TEC presented an enhancement to positive ΔTEC values as a result of the equatorward wind. With reversal of the wind to southward ΔTEC decreased (when ΔfoF2 showed decrease) at all the latitudes. Finally the ΔTEC turned negative with a time delay of a few hours with respect to the maximum in negative ΔhmF2 (poleward wind). Here we note that a poleward disturbance wind is an important cause of significant TEC decrease over low- to middle-latitude regions at least under night conditions.

5.2. Longitudinal/Local Time Dependences of the Disturbance Electric Fields

[29] An idea of the longitudinal/local time dependence of some important features of the disturbance electric fields can be obtained from a comparison of the *F* layer height variations over the equatorial sites CPN and SL in the two longitude sectors presented together with the *AE* variations in Figure 8. The *AE* intensification marking the storm onset at 0610 UT on 29 October is indicated in Figure 8. The associated polar cap potential drop corresponds to a dawn-dusk electric field that penetrates to equatorial latitudes until shield by the region 2 field-aligned currents. This under-shielded electric field has eastward polarity on the dayside and westward polarity on the nightside. The rapid *F* layer uplift under an eastward electric field over CPN on the dayside with the simultaneous rapid *F* layer descent due to westward electric field over SL on the nightside clearly characterizes this electric field phase relationship. The uplift

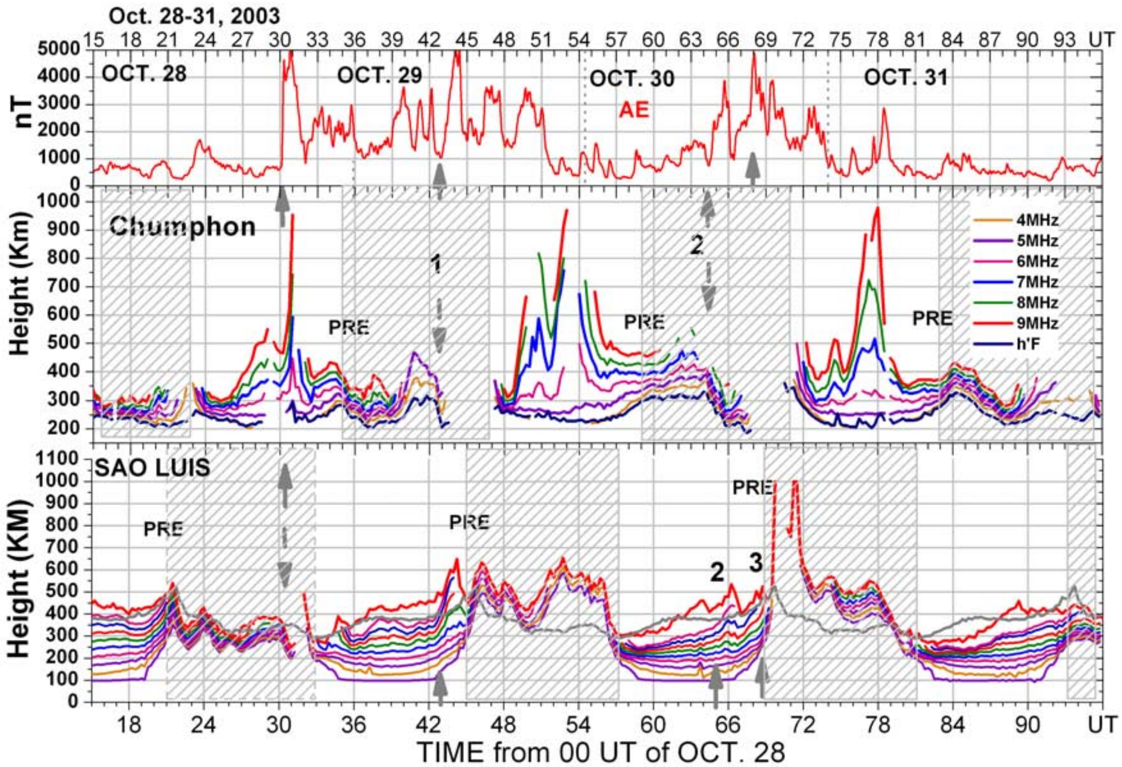

Figure 8. Plots (top) of the *AE* index, (middle) the virtual height of the *F* layer base, $h'F$, and virtual heights at specific plasma frequencies as in Figure 5 over Chumphon, and (bottom) true heights and hmF2 over Sao Luis as in Figure 2. The reference curve for hmF2 over Sao Luis is shown by gray curve. The shaded areas indicate local night hours.

of the *F* layer over CPN reached a maximum near 1400 LT/0700 UT and the corresponding vertical drift velocity was ~66 m s^{-1} as stated above. This may be an overestimate due to the use of virtual height in its derivation. (The role of photochemistry in the ionization balance of the daytime *F* layer might introduce some uncertainty in the vertical drift determined as $d(h'F))/dt$.) The downward drift velocity at ~0330 LT/0630 UT over Brazil as modeled using the SUPIM by *Batista et al.* [2006] was 130 m s^{-1}. Using a self-consistent Magnetosphere-Thermosphere-Ionosphere General Circulation Model (MTIEGSM) involving energy input at high latitude and associated polar cap expansion and contraction (that is, the polar cap potential drop build up and decay) phases *Richmond et al.* [2003] presented the magnetic local time dependence of the prompt penetrating/partially shielded electric field over equatorial latitudes [see also *Fejer et al.*, 1990; *Spiro et al.*, 1988]. The ratio of the nightside to the dayside electric fields (which is close to 2) in the present case is compatible with the corresponding value deduced from the model result of *Richmond et al.* [2003]. We must, however, be cautious that the validity of such a comparison is subject to the condition that the energy input function for the storm event under study is similar to that used for the model results by *Richmond et al.* [2003].

[30] In the cases of a dominant *AE* intensification episode that occurred at 1900 UT of 29 October (identified as 1 in Figures 5 and 8), when the Asian sector was on the nightside the PPE polarity relationship with SL has turned exactly opposite. The dawn-dusk polar cap electric field produces a westward PP electric field that caused a downward plasma drift (*F* layer descent) at ~02 AM over CPN (identified 1), whereas an eastward electric field caused the *F* layer uplift over SL that was in the afternoon sector (1600 LT). In this case the downward velocity over CPN is ~45 m s^{-1}, which appears to be equivalent of the 130 m s^{-1} modeled by *Batista et al.* [2006] for SL (considering that the height region of the vertical drift was similar in the two cases). The corresponding upward drift velocity over SL is ~45 m s^{-1}. Here again the ratio of the velocity magnitudes is roughly compatible with ratio obtained for the two corresponding local times in the results of *Richmond et al.* [2003] (as described above). The 1900 UT *AE* intensification was also responsible for the development of a westward electrojet current of significant intensity over Yap (Figure 5) starting at 0400 LT (discussed in section 5.3).

[31] Subsequent to the 1900 UT descent, the *F* layer over CPN suffered enhanced recombination loss resulting in the data interruption that made difficult a comparison of the electric field variations with those over the Brazilian sector where the evening prereversal electric field (PRE) appears to have been enhanced due to an eastward PPE arising from a rather weak (~700 nT) but very rapid *AE* intensification that occurred at 2100 UT/1800 LT.

[32] The *AE* intensification/recovery episode during ~0100–0330 UT of 30 October appears to have produced PPE variation that caused *F* layer height changes in opposite phases in the Asian and Brazilian longitudes. A larger change in the *F* layer heights that soon followed (starting

at ~0400 UT) appears to coincide with a rather weak intensity *AE* increase (~500 nT), which is in contrast to the significantly larger *AE* intensification to which the preceding height variations were attributed. Such cause-effect relationships discussed here may indicate that additional influence from intense disturbance equatorward winds could have been a factor in these cases, even though the magnetic dip angle of CPN is only 6° (Table 1). (It should be pointed out here that the ionosonde data plots at 15-min resolution could introduce some uncertainty in the precise identification of the event onset times in the *F* layer height parameter with respect to that of the *AE* plotted at 1-min time resolution.) The *F* layer height increase over SL (Figures 2 and 8) starting near 0300 UT/0000 LT (on 30 October), should be caused by a DDE that turns eastward around this local time [*Richmond et al.*, 2003]. It is interesting to note that the *AE* intensification/recovery episodes that occurred during the interval of 1400–2300 UT of 30 October produced PP electric fields of varying intensity and polarity, as indicated by the *F* layer height oscillations that are nearly in opposite phases on the Asian nightside (with loss of data) and Brazilian dayside-eveningside in much the same way as happened on the previous day. The most outstanding feature during this interval is the exceptionally large vertical uplift of the *F* layer over São Luís, which seems to be caused by a PPE arising from a rapid *AE* intensification at 2100 UT. The uplifted *F* layer trace reached to heights beyond the 1100 km range limit of the ionosonde for ~1 h. (The corresponding electric field changes over CPN appears to be dominated by intense westward electric field as indicated by the continuing loss of data caused by the large layer descent under the *AE* intensification episodes that preceded.) On the last day (31 October) of this disturbance interval the response features seem to characterize a situation of competing/complementary influences of both types of electric fields (PPE and DDE). In particular, an eastward DDE that developed during the postmidnight hours (as seen in the height increases starting at 1630 UT/2330 LT over CPN) was accompanied by a westward DDE in the evening over SL, as evidenced by the inhibition of the PRE (see Figure 8).

5.3. Nighttime Westward Electrojet Development

[33] The presunrise EEJ current development due to the *AE* intensifications that occurred on two consecutive days (29 and 30 October in UT) at the western Pacific longitudes (Figure 5) poses an important question as to the nighttime *E* layer conductivity required to drive such a current. The intensity of this current was around 30 nT which is nearly of the same amplitude as that of the afternoon eastward EEJ enhancement under an eastward PPE that occurred in response to the first *AE* intensification of 0610 UT storm onset. It may be noted that the *AE* intensifications that caused the two EEJ enhancement episodes of similar intensity (that of the 1510 LT of 29 October and of the ~0400 LT of 30 October), also presented similar degree of intensification (although the rates of *AE* increases were somewhat different in the two cases). Therefore it should be possible to estimate the nighttime *E* layer conductivity that permitted the presunrise westward EEJ current as follows. The increase/decrease in magnetic field horizontal component ΔH is proportional to the change in the EEJ current ΔI induced by a prompt penetrating electric field E_{PP} such that

$$\Delta H \propto \Delta I = E_{PP}\ \sigma_C \qquad (1)$$

where σ_C is the Cowling conductivity. Considering that the E_{PP} is a function of the *AE* intensity through a local time-dependent efficiency factor ε for the prompt penetration of polar electric field to equatorial latitude, we can replace E_{PP} by εAE. Identifying by t1 and t2 the two local times (1510 LT and 0400 LT, respectively) of the ΔH episodes that have the same/similar intensity we may rewrite the above relationships as

$$\varepsilon_{t1} AE_{t1} \sigma_{Ct1} = \varepsilon_{t2} AE_{t2} \sigma_{Ct2} \qquad (2)$$

From the *AE* plots (Figure 1) it is reasonable to assume that $AE_{t1} = AE_{t2}$ so that we have

$$\sigma_{Ct2} = \sigma_{Ct1}(\varepsilon_{t1}/\varepsilon_{t2}) \qquad (3)$$

The results of *Richmond et al.* [2003] on the undershielding/PPE over equatorial latitude, during the main phase of a storm as simulated using the MTIEGCM can be used to determine the ratio of the electric field penetration efficiencies at the two local time of our interest here. From their Figure 4 that presents the magnetic local time dependence of this disturbance electric field we can determine the ratio of the electric field at 1510 LT to that of 0400 LT, which is equivalent to $\varepsilon_{t1}/\varepsilon_{t2}$, to be 0.5/2.25 = 0.2. This result gives an estimate of the σ_C required for the flow of the westward EEJ at 0400 LT as around 20 percent of its value at 1510 LT. The same fraction (20%) also applies to the electron densities (n_e) at the two local times (0400 LT and 1510 LT), since $\sigma_C \propto n_e$. Using the foE at 1510 LT as obtained from recently available daytime foE measurement by ionosonde at near equatorial sites [*Abdu et al.*, 2004], the electron density ($n_e \propto$ foE^2) at 0400 LT can be evaluated as $\sim 6 \times 10^3$ cm^{-3}. This value is somewhat higher than the presently known values for quiet time night *E* layer for this local time, based on modeling and observational results, which is around 3×10^3 cm^{-3} as given by *Titheridge* [2001] as well as close to the value represented in the IRI-95 [*Bilitza*, 1990]. This larger than normal values may be attributed to the disturbed condition for which a possible source of the enhanced ion production needs to be identified. A westward EEJ current occurred over Yap also during the postmidnight-presunrise hours of 31 October. Here the current intensity at 2000 UT (0500 LT) was comparable to that of the previous night, while at the same time the associated *AE* intensification showed similar intensity as in the previous episodes. Therefore the consideration on the requirement of the σ_C for this case is similar to that discussed above.

5.4. Equatorial Anomaly Development Due to Undershielding/Overshielding Electric Fields

[34] TEC enhancements associated with the equatorial anomaly development arising from the disturbance eastward electric fields during this storm sequence had the largest intensity in the afternoon sector over the eastern Pacific

region (westward of American longitudes) where large latitudinal expansion of the EIA crest with TEC exceeding 250 TEC units were observed [*Mannucci et al.*, 2005; *Zhao et al.*, 2005; *Lin et al.*, 2005a]. The EIA TEC enhancements were of relatively smaller intensity in the Asian as well as Brazilian longitudes largely due to local time dependence of the disturbance electric fields. The EIA developments of moderate intensity observed over the two longitude sectors analyzed here can be attributed to both the undershielding as well as the overshielding electric fields arising from specific *AE* growth and recovery phases. An interesting case of an EIA development due to an overshielding eastward electric field (associated with an *AE* recovery following an intensification) was discussed by *Batista et al.* [2006]. This concerned the case of the large foF2 enhancement at 0900–1000 UT (0600–0700 LT) on 29 October over CP shown in Figure 4. In this case a time delay of 1–2 h for the large (anomalous) foF2 increase with respect to the *AE* recovery process (during 0700–0800 UT) may be noted. This delay factor can be attributed to the response time for the plasma distribution/density adjustment through diffusion process in the flux tubes involved in the anomaly formation. A similar situation appears to exist during an *AE* recovery phase that occurred at ~2200 UT of 30 October (see Figure 1). The Asian longitudes at this time were in the 0500–0700 LT sector. Here the *AE* recovery has given rise to an overshielding eastward electric field as is evident in the EEJ current reversal to eastward over Yap (identified as 3 in Figure 5), the *F* layer height increases over CPN (that was possibly obscured due to the disappearance of the *F* layer mentioned 4.2.1) and that over OKI (Figure 6a). The corresponding height responses over YAM and KOK were weaker and probably modulated by winds. This height increase appears to be responsible for an EIA development as can be noted in the significant increase of ΔfoF2 (around 2230 UT/0730 LT) over OKI in Figure 6b (with smaller ΔfoF2 amplitudes at YAM and KOK as well). The ΔTEC (Figure 7) also showed significant EIA development. Here we note a case of EIA development in morning hours in the Asian sector, due to an overshielding eastward electric field exactly similar to the EIA development in similar circumstances (overshielding electric field) in the Brazilian morning sector (on 29 October).

[35] The 2100 UT (of 30 October) *AE* intensification whose recovery was the source of the overshielding electric field that caused the EIA development in the Asian morning sector, was responsible for a strong undershielding electric field in the Brazilian evening sector where intense EIA development seems to have occurred. The large *F* layer uplift that occurred on the evening over Brazil was the result of this undershielding eastward electric field (discussed in section 4.1). This event produced severe plasma depletion simultaneously at latitudes extending to CP, as can be noted in the Figures 2, 3, and 4. (In the case of Fz the foF2 values appear to have been severely affected by spread *F* traces that were less severe at SL and CP.) It appears that the anomaly peak has moved to higher latitudes poleward of CP under a giant fountain, as seen also in the GPS-TEC map for this region (not shown here). At the corresponding local time (0600 LT) in the Asian sector the expected response (as per model) is a westward electric field which appears to be consistent with the westward EEJ over Yap and the decrease in hmF2 deviations over Japanese stations starting at 0600 LT/2100 UT. (Over CPN the data were interrupted.) This height decrease (negative ΔhmF2) appears to have caused some decrease of ΔfoF2 over OKI and YAM (Figure 6b). (The larger ΔfoF2 decrease at higher latitudes appears to be arising from the disturbance winds.) Thus we note that during these event sequences both the undershielding electric field associated with the *AE* intensification as much as the overshielding electric field that characterizes the *AE* recovery appears to have caused developments of the equatorial anomaly in the Brazilian as well as in the Asian Brazilian longitude sectors, respectively.

5.5. Considerations on Disturbance Winds and Dynamo Electric Field Longitudinal Distribution/Dependence

[36] The interrelated hmF2 and foF2 variations can be used to infer further aspects of disturbance winds and electric fields in the two longitudinal sectors. Over equatorial latitudes the plasma fountain (under an eastward PP electric field) could cause *F* layer plasma density decrease producing anticorrelated changes in the hmF2 and foF2. A good example is the case of large evening *F* layer uplift over SL (on 30 October) that produced a rapid decrease of foF2 (Figure 2). Such changes (but to a smaller degree) was observed also on the evening of 29 October over SL. Very similar response features where observed over CPN (Figure 5) at the beginning of the storm (0610 UT) and at a few other instances during daytimes of 30 and 31 October (Figure 5). Conversely a decrease in the *F* layer height due to a westward electric field should cause an increase of foF2 as is generally observed. However, a rapid decrease of the height due to a large westward electric field as happened during the 0610 UT storm onset resulted in a significant decrease of foF2 over SL. This arises due to the enhanced recombination loss of plasma at the lower heights reached by the layer, and as such a certain delay in the foF2 response with respect to height decrease (the order of 1 h in this case) may be noted. Such response features are observed also over CPN on the nights of 29–30 and 30–31 October (in UT). A relatively smaller westward electric field driving a reverse fountain could cause foF2 enhancement over equator. Thus the larger than normal foF2 during daytime over SL and Fz (Figures 2 and 3) indicates the role of a westward disturbance dynamo electric field that appears to be present for most part of the daytime on 29, 30, and 31 October. The less than normal foF2 over CP (Figure 4) during the same time intervals (with some exceptions) is consistent with presence of such a DD electric field over Brazil. On the other hand, the smaller than normal foF2 over CPN during the day hours of 29 (starting with the SSC), 30, and 31 October would indicate the dominating presence of an eastward PPE over the Asian equatorial region. Obviously such contrasting situation is the result of the UT distribution of the *AE* episodes falling in predominantly day or night sectors in the two longitude sectors.

[37] The effect of disturbance meridional winds on the *F* layer parameters increases toward midlatitudes from the equator. Thus the ΔhmF2 that is generally positive over the Japanese stations (Figure 6a) would suggest the presence of equatorward winds dominating most of the time during these storm events [see also *Buonsanto and Foster*, 1993].

Over CP, which is a low-latitude station similar to OKI in Japan, we may note such equatorward winds dominating during the evening and night hours. See for example the higher than quiet time hmF2 from the midday of 29 October to the morning of 30 October and again from the midday of 30 October to the morning of 31 October in Figure 4 (although partially contaminated by DD electric field) that roughly correspond to postmidnight to evening hours over Asia. We thus have a situation of disturbance meridional winds converging toward equator for extended durations, if not for most of the disturbance interval of this study. The resulting ionization "pileup" over the equator could modify "topside" density profile involving increase of hmF2 which otherwise is dominantly controlled by the $\mathbf{E} \times \mathbf{B}$ action of a zonal electric field. Thus an expected lower than normal hmF2 corresponding to an increased foF2 indicative of a westward DD electric field (which is expected to be present) may not be readily observed over SL as it appears to be the case for considerable intervals on 29, 30 and 31 October.

[38] An interesting picture of disturbance global wind pattern can be inferred by comparing the hmF2 variations over CP and Japanese ionososnde network, in the recovery phase of this storm sequences. The hmF2 presented a large and rapid descent over CP in the morning ($\sim$0600 LT/0900 UT) of 31 October (Figure 4) which indicated the presence of an intense poleward (southward) wind. This appears to heave caused a large decrease of foF2 by recombination loss process. At the same UT when it is evening over Japan we note an increase in ΔhmF2 starting at $\sim$1800 LT, sunset (with amplitude increasing toward higher latitudes, Figure 6a) that suggests a rapid increase of equatorward wind into the night. This wind reversed direction to poleward at around 1400 UT, just around midnight over Japan, while at the same time the disturbance wind over CP reversed to equatorward/northward just around midday over Brazil (as indicated by the increase/recovery of hmF2 toward the quiet time value). This gives us a picture of a transient surge of transequatorial wind simultaneously over the Japanese and Brazilian longitudes first directed southward followed by its reversal to northward, the whole episode lasting for about 6 h. Such cases of global-scale transequatorial disturbance winds could arise from an asymmetry in the storm energy input and electrojet heating process between the north and south auroral regions. (North-south asymmetry in the energy input, as observed from DMSP F13 and F15 satellites during these storm events, has been reported by *Zhao et al.* [2005].) It may be noted further that during this episode the foF2 over OKI increased by $\sim$12 MHz above normal, while it decreased by 8 MHz below normal over CP.

6. Conclusions

[39] We have analyzed ionospheric data sets from Brazilian and Asian-Japanese longitude sectors during the super magnetic storm events of 28–31 October 2003. The analysis focused on disturbance electric fields that promptly penetrate to equatorial latitudes at the different storm phases identified by *AE* intensifications and recoveries, and their local time and longitudinal dependences. The analysis also covered effects from the delayed and longer-lasting wind dynamo electric field that dominates the low latitudes and the associated disturbance winds that propagate to equatorial latitudes from the source of generation at high latitudes. The observational results on the disturbance electric field characteristics were discussed in the light of the more recent global model (MTIEGCM) simulation by *Richmond et al.* [2003] showing generally good agreement in the local time dependence of the electric field polarity between the observation and model. The significant storm time modifications of the major phenomenology of the equatorial-low-middle-latitude ionosphere in terms of their local time and longitude dependences were interpreted based on the storm phases and the intensity of the associated auroral electrojet activity. We have presented for the first time observational evidence on the development of nighttime westward equatorial electrojet current due to strong prompt penetrating westward electric field originating from auroral electrojet current intensification episodes. The main conclusions of the present study can be highlighted as follows:

[40] 1. Auroral intensifications produce prompt penetrating electric field with strong local time dependence, with eastward electric field on the dayside and eveningside and westward electric field during most of the night hours in agreement with recent model simulations. It is not clear how the intensity of the penetrating electric field can be dependent on the time rate of change of the *AE* intensification. The *AE* recovery that follows an intensification causes penetrating electric field of opposite polarity. The disturbance electric field polarity local time dependence as inferred from our analysis of ionosonde data is in general agreement with the recent MTIEGCM simulation results presented by *Richmond et al.* [2003].

[41] 2. The *AE* intensification occurring at sunset hours in the Brazilian sector produces intense zonal (eastward) electric field causing abnormal and larger *F* layer uplift than was observed over Asian sector during this or any previous storm events.

[42] 3. A prompt penetrating westward electric field occurring during the postmidnight hours (studied here) could lead to development of westward electrojet current, suggesting the presence of enhanced storm time *E* layer conductivity over the Pacific equatorial station Yap analyzed in this study.

[43] 4. The continuing storm activity is marked by disturbance dynamo electric field accompanied by strong disturbance meridional winds that are directed equatorward for most of the time (with some exceptions) in both Asian and Brazilian longitude sectors.

[44] 5. There is some evidence in support of previous findings that disturbance meridional winds could limit latitudinal extension of spread *F*/plasma bubble development.

[45] 6. Equatorial anomaly development was observed to be driven by undershielding electric field (*AE* intensification) during evening/postsunset hours and by overshielding electric field (*AE* recovery) during presunrise and morning hours. EIA inhibition during postmidnight hours was observed as caused by PPE of westward polarity. Such developments were often strongly modulated by disturbance meridional winds, however.

[46] 7. The intensity of a TEC storm over low to middle latitudes produced by an eastward prompt penetrating electric field can be significantly enhanced by an equatorward directed disturbance wind under daytime conditions, and conversely, a poleward wind can cause significant

decrease in the TEC at least during nighttime. In either case the TEC response time is of the order of 2–3 h with respect to an imposed driving force (disturbance electric fields or winds).

[47] 8. There is evidence as inferred from F2 layer height characteristics that transients of intense transequatorial winds flipping direction from southward to northward were present during the recovery phase of the last of the three *Dst* storms. Such transients appears to be occurring on a global scale since they are observed simultaneously over both the Brazilian and Asian longitude sectors, thus suggesting the possibility of strong asymmetry in the auroral energy input between north and south hemispheres. Disturbance winds converge toward equator for most of the storm duration, however.

[48] **Acknowledgments.** The authors wish to acknowledge the support from FAPESP through the project 1999/00437-0 and CNPq through grants 502804/2004-1 and 500271/2003-8. The 1-min *AE* values used in this paper were provided by B. Zhao (Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing, China) for which we express our profound thanks. The authors are grateful to M. Kunitake for preparing geomagnetic data. The Chumphon ionosonde station is operated with the cooperation of the National Institute of Information and Communications Technology, Japan, and King Mongkut's Institute of Technology Ladkrabang, Thailand.

[49] Amitava Bhattacharjee thanks Charles Lin and another reviewer for their assistance in evaluating this paper.

References

Abdu, M. A. (1997), Major phenomena of the equatorial ionosphere-thermosphere system under disturbed conditions, *J. Atmos. Sol. Terr. Phys.*, *59*, 1505–1519.

Abdu, M. A., G. O. Walker, B. M. Reddy, J. H. A. Sobral, B. G. Fejer, T. Kikuchi, N. B. Trivedi, and E. P. Szuszczewicz (1990), Electric field versus neutral wind control of the equatorial anomaly under quiet and disturbed conditions: A global perspective from SUNDIAL 86, *Ann. Geophys.*, *8*, 419–430.

Abdu, M. A., I. S. Batista, G. O. Walker, J. H. A. Sobral, N. B. Trivedi, and E. R. de Paula (1995), Equatorial ionospheric electric fields during magnetospheric disturbances: Local time/longitudinal dependencies from recent EITS campaigns, *J. Atmos. Terr. Phys.*, *57*, 1065–1083.

Abdu, M. A., J. H. Sastri, J. MacDougall, I. S. Batista, and J. H. A. Sobral (1997), Equatorial disturbance dynamo electric field longitudinal structure and spread F: A case study from GUARA/EITS campaigns, *Geophys. Res. Lett.*, *24*, 1707–1710.

Abdu, M. A., I. S. Batista, H. Takahashi, J. MacDougall, J. H. Sobral, A. F. Medeiros, and N. B. Trivedi (2003), Magnetospheric disturbance induced equatorial plasma bubble development and dynamics: A case study in Brazilian sector, *J. Geophys. Res.*, *108*(A12), 1449, doi:10.1029/2002JA009721.

Abdu, M. A., I. S. Batista, B. W. Reinisch, and A. J. Carrasco (2004), Equatorial F layer heights, evening prereversal electric field and night E-layer density in the American sector: IRI validation with observations, *Adv. Space Res.*, *34*, 1953–1965.

Abdu, M. A., K. N. Iyer, R. T. de Medeiros, I. S. Batista, and J. H. A. Sobral (2006a), Thermospheric meridional wind control of equatorial spread F and evening prereversal electric field, *Geophys. Res. Lett.*, *33*, L07106, doi:10.1029/2005GL024835.

Abdu, M. A., J. R. de Souza, J. H. A. Sobral, and I. S. Batista (2006b), Magnetic storm associated disturbance dynamo effects over low and equatorial latitude *F*-region, in *Recurrent Magnetic Storms: Corotating Solar Wind Streams*, *Geophys. Monogr. Ser.*, vol. 167, edited by B. Tsurutani et al., pp. 283–304, AGU, Washington, D. C.

Bailey, G. J., R. Selleck, and Y. Ripeth (1993), A modeling study of the equatorial topside ionosphere, *Ann. Geophys.*, *II*, 263–272.

Basu, S., Su. Basu, K. M. Groves, E. MacKenzie, M. J. Keskinen, and F. J. Rich (2005), Near-simultaneous plasma structuring in the midlatitude and equatorial ionosphere during magnetic superstorms, *Geophys. Res. Lett.*, *32*, L12S05, doi:10.1029/2004GL021678.

Basu, Su., et al. (2005), Two components of ionospheric plasma structuring at midlatitudes observed during the large magnetic storm of October 30, 2003, *Geophys. Res. Lett.*, *32*, L12S06, doi:10.1029/2004GL021669.

Batista, I. S., E. R. de Paula, M. A. Abdu, N. B. Trivedi, and M. E. Greenspan (1991), Ionospheric effects of the March 13, 1989, magnetic storm at low and equatorial latitudes, *J. Geophys. Res.*, *96*, 13,943–13,952.

Batista, I. S., M. A. Abdu, J. R. Souza, F. Bertoni, M. T. Matsuoka, P. O. Camargo, and G. J. Bailey (2006), Unusual early morning development of the equatorial anomaly in the Brazilian sector during the Halloween magnetic storm, *J. Geophys. Res.*, *111*, A05307, doi:10.1029/2005JA011428.

Bilitza, D. (1990), International Reference Ionosphere 1990, *Rep. 90-22*, Natl. Space Sci. Data Cent., World Data Cent. A for Rocket and Satell., NASA Goddard Space Flight Center, Greenbelt, Md.

Blanc, M., and A. D. Richmond (1980), The ionospheric disturbance dynamo, *J. Geophys. Res.*, *85*, 1669–1686.

Buonsanto, M. J., and J. C. Foster (1993), Effects of magnetospheric electric fields and neutral winds on the low-middle latitude ionosphere during the March 20–21, 1990 storm, *J. Geophys. Res.*, *98*, 19,133–19,140.

Fejer, B. G., and L. Scherliess (1997), Empirical models of storm time equatorial zonal electric fields, *J. Geophys. Res.*, *102*, 24,047–24,056.

Fejer, B. G., et al. (1990), Low and midlatitude ionospheric electric fields during the January 1984 Gismos campaign, *J. Geophys. Res.*, *85*, 2367–2377.

Foster, J. C., A. J. Coster, P. J. Erickson, W. Rideout, F. J. Rich, T. J. Immel, and B. R. Sandel (2005), Redistribution of the stormtime ionosphere and the formation of a plasmasphere bulge, in *Inner Magnetosphere Interactions New Perspective from Imaging*, *Geophys. Monogr. Ser.*, vol. 159, edited by J. L. Burch, M. Schulz, and H. Spence, pp. 277–290, AGU, Washington, D. C.

Fuller-Rowell, T. J., G. H. Millward, A. D. Richmond, and M. V. Codrescu (2002), Storm-time changes in the upper atmosphere at low latitude, *J. Atmos. Sol. Terr. Phys.*, *64*, 1383–1391.

Gopalswamy, N., L. Barbieri, G. Lu, S. P. Plunkett, and R. M. Skoug (2005), Introduction to the special section: Violent Sun-Earth connection events of October–November 2003, *Geophys. Res. Lett.*, *32*, L03S01, doi:10.1029/2005GL022348.

Greenspan, M. E., C. E. Rasmussen, W. J. Burke, and M. A. Abdu (1991), Equatorial density depletions observed at 840 km during the great magnetic storm of March 1989, *J. Geophys. Res.*, *96*, 13,931–13,942.

Huang, C.-S., J. C. Foster, and M. C. Kelley (2005), Long-duration penetration of the interplanetary electric field to the low-latitude ionosphere during the main phase of magnetic storms, *J. Geophys. Res.*, *110*, A11309, doi:10.1029/2005JA011202.

Immel, T. J., J. C. Foster, A. J. Coster, S. B. Mende, and H. U. Frey (2005), Global storm time plasma redistribution imaged from the ground and space, *Geophys. Res. Lett.*, *32*, L03107, doi:10.1029/2004GL021120.

Jaggi, R. K., and R. A. Wolf (1973), Self-consistent calculation of the motion of a sheet of ions in the magnetosphere, *J. Geophys. Res.*, *78*, 2852–2866.

Kelley, M. C., B. G. Fejer, and C. A. Gonzales (1979), An explanation for anomalous ionospheric electric fields associated with a northward turning of the interplanetary magnetic field, *Geophys. Res. Lett.*, *6*, 301–304.

Kikuchi, T., H. Luhr, T. Kitamura, O. Saka, and K. Schliegel (1996), Direct penetration of the polar electric field to the equator during a DP2 event as detected by the auroral and equatorial magnetometer chains and the EISCAT radar, *J. Geophys. Res.*, *101*, 17,161–17,173.

Lin, C. H., A. D. Richmond, J. Y. Liu, H. C. Yeh, L. J. Paxton, G. Lu, H. F. Tsai, and S.-Y. Su (2005a), Large-scale variations of the low-latitude ionosphere during the October–November 2003 superstorm: Observational results, *J. Geophys. Res.*, *110*, A09S28, doi:10.1029/2004JA010900.

Lin, C. H., A. D. Richmond, R. A. Heelis, G. J. Bailey, G. Lu, J. Y. Liu, H. C. Yeh, and S.-Y. Su (2005b), Theoretical study of the low- and midlatitude ionospheric electron density enhancement during the October 2003 superstorm: Relative importance of the neutral wind and the electric field, *J. Geophys. Res.*, *110*, A12312, doi:10.1029/2005JA011304.

Mannucci, A. J., B. T. Tsurutani, B. A. Iijima, A. Komjathy, A. Saito, W. D. Gonzalez, F. L. Guarnieri, J. U. Kozyra, and R. Skoug (2005), Dayside global ionospheric response to the major interplanetary events of October 29–30, 2003 "Halloween Storms," *Geophys. Res. Lett.*, *32*, L12S02, doi:10.1029/2004GL021467.

Maruyama, T. (1988), A diagnostic model for equatorial spread F: 1. Model description and application to electric field and neutral wind effects, *J. Geophys. Res.*, *93*, 14,611–14,622.

Maruyama, T., G. Ma, and M. Nakamura (2004), Signature of TEC storm on 6 November 2001 derived from dense GPS receiver network and ionosonde chain over Japan, *J. Geophys. Res.*, *109*, A10302, doi:10.1029/2004JA010451.

Pincheira, X. T., M. A. Abdu, I. S. Batista, and P. G. Richards (2002), An investigation of ionospheric responses, and disturbance thermospheric winds, during magnetic storms over South American sector, *J. Geophys. Res.*, *107*(A11), 1379, doi:10.1029/2001JA000263.

Prolss, G. W. (1997), Magnetic storm perturbations of the upper atmosphere, in *Magnetic Storms*, *Geophys. Monogr. Ser.*, vol. 98, edited by B. T. Tsurutani et al., pp 227–241, AGU, Washington, D. C.

Reinisch, B. W., K. Bibl, D. F. Kitrosser, G. S. Sales, J. S. Tang, Z.-M. Zhang, T. W. Bullet, and J. A. Ralls (1989), The digisonde 256 ionospheric sounder, in *World Ionosphere/Thermosphere Study*, *WITS Handb.*, vol. 2, edited by C. H. Liu, pp. 350–366, Sci. Comm. on Sol.-Terr. Phys., Urbana, Ill.

Richmond, A. D., C. Peymirat, and R. G. Roble (2003), Long-lasting disturbances in the equatorial ionospheric electric field simulated with a coupled magnetosphere-ionosphere-thermosphere model, *J. Geophys. Res.*, *108*(A3), 1118, doi:10.1029/2002JA009758.

Sahai, Y., et al. (2005), Effects of the major geomagnetic storms of October 2003 on the equatorial and low-latitude *F* region in two longitudinal sectors, *J. Geophys. Res.*, *110*, A12S91, doi:10.1029/2004JA010999.

Sastri, J. H. (1988), Equatorial electric fields of ionospheric disturbance dynamo origin, *Ann. Geophys.*, *6*, 635–642.

Sastri, J. H., K. Niranjan, and K. S. V. Subbarao (2002), Response of the equatorial ionosphere in the Indian (midnight) sector to the severe magnetic storm of July 15, 2000, *Geophys. Res. Lett.*, *29*(13), 1651, doi:10.1029/2002GL015133.

Scherliess, L., and B. G. Fejer (1997), Storm time dependence of equatorial disturbance dynamo zonal electric fields, *J. Geophys. Res.*, *102*, 24,037–24,046.

Sobral, J. H. A., M. A. Abdu, W. D. Gonzalez, B. T. Tsurutani, I. S. Batista, and A. L. C. Gonzalez (1997), Effects of intense storms and substorms on the equatorial ionosphere/thermosphere system in the American sector from ground-based and satellite data, *J. Geophys. Res.*, *102*, 14,305–14,314.

Spiro, R. W., R. A. Wolf, and B. G. Fejer (1988), Penetration of high latitude electric field effects to low latitudes during SUNDIAL 1984, *Ann. Geophys.*, *6*, 39–50.

Titheridge, J. E. (2001), Production of the low-latitude night E layer, *J. Geophys. Res.*, *106*, 12,781–12,786.

Tsurutani, B., et al. (2004), Global dayside ionospheric uplift and enhancement associated with interplanetary electric fields, *J. Geophys. Res.*, *109*, A08302, doi:10.1029/2003JA010342.

Vasyliunas, V. (1972), The inter-relationship of magnetospheric processes, in *Earth's Magnetospheric Processes*, edited by B. M. McCormack, pp. 29–38, Springer, New York.

Zhao, B., W. Wan, and L. Liu (2005), Response of equatorial anomaly to the October–November 2003 superstorm, *Ann. Geophys.*, *23*, 693–706.

M. A. Abdu and I. S. Batista, Instituto Nacional de Pesquisas Espaciais, Divisao de Aeronomia, Ave. dos Astronautas 1578, 970 São José dos Campos, Sao Paulo 12201-970, Brazil.

T. Maruyama, M. Nakamura, and S. Saito, National Institute of Information and Communication Technology, -1 Nukuikita 4-chome, Koganei, Tokyo, 184-8795, Japan.